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1. Your reference	441GB
2. Patent application number *(The Patent Office will fill in this part)*	**9907868.5**
3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	Renishaw plc New Mills Wotton-under-Edge Gloucestershire GL12 8JR
Patents ADP number *(if you know it)*	2691002
If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
4. Title of the invention	Method of Calibrating A Scanning System
5. Name of your agent *(if you have one)*	J Waite et al
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Renishaw plc, Patent Department New Mills Wotton-under-Edge Gloucestershire GL12 8JR
Patents ADP number *(if you know it)*	2600005 2691002

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
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7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application	Date of filing *(day / month / year)*
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8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* *a) any applicant named in part 3 is not an inventor, or* *b) there is an inventor who is not named as an applicant, or* *c) any named applicant is a corporate body.* *See note (d))*	Yes

9. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form	
Description	12
Claim*(s)*	0
Abstract	0
Drawing*(s)*	2 + 2

10. If you are also filing any of the following, state how many against each item.

Priority documents	0
Translations of priority documents	0
Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	0
Request for preliminary examination and search *(Patents Form 9/77)*	0
Request for substantive examination *(Patents Form 10/77)*	0
Any other documents *(please specify)*	0

11. I/We request the grant of a patent on the basis of this application.

Signature J Waite . Date 07.04.1999

AGENT FOR THE APPLICANT

12. Name and daytime telephone number of person to contact in the United Kingdom

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b) *Write your answers in capital letters using black ink or you may type them.*

c) *If there is not enough space for all the relevant details on any part of this form, please continue on a separate sheet of paper and write "see continuation sheet" in the relevant part(s). Any continuation sheet should be attached to this form.*

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METHOD OF CALIBRATING A SCANNING SYSTEM

The present invention relates to a method of calibrating a scanning system. A scanning system in this specification should be understood to mean a combination of a machine and a probe which together are capable of use in scanning an artefact in order to obtain information about its size, shape or surface contours. The machine may be a co-ordinate measuring machine (CMM), or robot, and the probe is preferably an analogue probe having a workpiece-contacting stylus. The machine has measuring devices for measuring the movement of the machine parts in three nominally orthogonal directions (referred to as X,Y and Z axes), and the probe includes measuring transducers for producing outputs indicative of the deflection of the probe stylus in three nominally orthogonal directions (referred to as the a,b and c axes).

In general terms the present invention relates to a method of calibrating a scanning system dynamically, whereby errors in the system produced when scanning an artefact at different scanning speeds (and hence at difference accelerations) may be mapped.

Methods of correcting machines for acceleration induced errors are known.

One example of such a method is described in European Patent No. 318557. In this method a first article from a batch of nominally identical articles is scanned at a relatively slow speed, noting the measurements of the positions of a number of datum points on the article. The scanning operation is repeated at a relatively fast speed noting the measurements of the positions of the same points. Any difference in the measurements are noted as errors in a correction table.

Thereafter all of the articles are scanned at the

relatively fast speed taking measurements of the positions of corresponding points on each article, and these measurements are corrected for machine accelerations using the previously noted errors.

Another example of such a method is described in US Patent No. 5,594,668. This patent discloses scanning a ring gauge at different velocities, and hence at different accelerations of the machine slides, and determining the differences in the measured X,Y values of a plurality of datum points as a function of the acceleration components of the machine in the X and Y directions. These measurements are repeated with the ring gauge positioned at several different places in the machine's working envelope, and a set of correction data is stored for subsequent correction of the measurements of workpieces.

We have found that stylus slippage on the surface being used for the calibration can be a source of significant errors in the measurements of the positions of the points on the surface which are used as the datum points, leading to errors in the calibration/correction data.

The errors occur because the simple correlation assumed between the three nominally orthogonal X,Y and Z axes of the machine and the three nominally orthogonal a,b and c axes of the probe is destroyed by stylus slippage.

Stylus slippage occurs when, for whatever reason, the probing force component in a direction in the plane of the surface contacted would otherwise exceed the product of the force component in the direction normal to the surface and the effective friction coefficient. Such a situation can arise from one or more reasons, e.g. the commanded machine direction may not be exactly normal to the contacted surface, and/or machine inaccuracies may lead to the machine not travelling accurately in the commanded direction, and/or probe inaccuracies (or design) may cause

the probing force direction to differ from the probe deflection direction.

Machine inaccuracies can lead to the machine not travelling along the commanded direction accurately enough to prevent slippage.

The present invention includes a method of calibrating a scanning system in which the effects of stylus slippage caused by probe and/or machine inaccuracies are minimised.

According to one aspect of the present invention there is provided a method of calibrating a scanning system comprising the following steps:

a) moving the probe stylus towards a surface of an artefact in a direction which is nominally normal to the surface, and contacting the surface at a number (N) of specific datum points on the surface,

b) using only the components of machine movements and probe stylus deflections which are normal to the surface at the points of contact therewith, making a determination of the positions of each of the datum points at the instant that the stylus tip is just in contact with the surface,

c) scanning the surface of the artefact at a predetermined finite probe stylus deflection and at a plurality of different speeds each time nominally passing through the datum points several times,

d) using the components of machine movements and probe stylus deflections which are normal to the surface, making further determinations of the apparent positions of each of the (N) datum points, and recording any differences in the normal direction from the positions determined in step b) for each speed,

e) from the differences recorded in step d) identifying the highest scanning speed at which the variations in the measurements of the positions of the datum points noted during each scan remain within a predetermined tolerance,

f) storing the identified speed and the differences in the measurement at that speed.

The method according to the invention is based on two theories. The first is that there can be no stylus slippage in the directions normal to the surface of the artefact. All stylus slippage must be parallel to the surface. The second is that the above-mentioned probe inaccuracies become negligible when the probe deflection is zero.

Thus by utilising only the components of machine movement and stylus deflection which are normal to the surface and determining these values when the stylus is just in contact with the surface, but has not started to deflect, the resulting measurements of the datum points are free of probe errors, and free of errors due to stylus slippage.

The determination of the position of each datum point at the instant the stylus tip is just in contact with the surface of the artefact may be achieved by driving the probe into the surface and synchronously recording the components of machine movements and probe deflections which are normal to the surface until the probe deflection reaches a predetermined limit. The recorded values are then extrapolated back to determine the position of the machine in the direction normal to the surface when the stylus was just in contact with the surface.

Alternatively, and preferably, the probe is driven into the surface until the stylus deflection reaches a predetermined limit and is then reversed at a known and controlled low

velocity. During the reversal the components of machine movements and probe deflections normal to the surface are recorded synchronously until the stylus leaves the surface. The recorded values are then extrapolated to determine the position of the machine in the direction normal to the surface when the stylus just left the surface. This is effectively the same as the position when the stylus just contacted the surface.

During the scanning step, the outputs of the measuring transducers of the probe in the a,b, and c axes are transformed into incremental values of X,Y,and Z using a probe transformation matrix.

Once the maximum scanning speed has been established by this method a map of the errors in the direction normal to the surface at the (n) points can be stored along with the data relating to the scanning speed, the particular artefact or feature, the particular CMM and the part location and orientation on the CMM, the particular probe and stylus configuration, and the probe matrix and nominal probe deflection used.

Instead of storing this data in the machine computer, possibly along with many other error maps for other workpieces, in accordance with a novel feature of the invention, this data may be stored outside of the machine as part of, or in association with, the part program associated with a workpiece. A part program is the software program which is loaded into the computer of a measuring machine when a workpiece is to be measured, and which identifies to the measuring machine both the details of workpiece to be measured, and the moves to be accomplished by the machine in order to make the required measurements.

Preferred embodiments of the invention will now be more particularly described with reference to the accompanying drawings in which:

Fig 1 illustrates a scanning system including a probe head attached to the quill of a CMM on which is mounted a scanning probe in position for measuring a bore in a workpiece,

Fig 2 illustrates in principle the relationship between the radial position of the CMM and the radial deflection of the stylus of the probe during a measurement step of the method of the invention,

Fig 3 illustrates the a and b axis outputs of an imperfect probe when the machine is reversed during the measuring step, and

Figs 4a and 4b illustrate respectively the actual output components of the probe displacement vector in the estimated radial and tangential directions when the direction of the movement of the CMM is not exactly radial, compared with the outputs when the radial component is truly radial.

Referring now to Fig 1, there is shown a probe head 1 mounted on a machine quill 10. The probe head carries a measuring probe 2 which has a stylus 3 with a stylus ball 4 at its free end. The stylus is shown in contact with a bore in a workpiece 5. The bore has nominal radius R and has its centre O at a nominal position X_c, Y_c, and Z_c in the machine axis coordinates. The stylus ball has a radius r which is predetermined.

As a first step in the calibration method the probe may be "zeroed" in its free condition. This simply involves taking readings from the probe measurement transducers when there is no contact or inertial force acting on the stylus, and setting these to zero in all three axes, or alternatively, storing these readings so that they can be subtracted from all subsequent readings. Note that multiple readings may need to be taken and averaged to take account of noise, vibration etc of the machine.

In a further, preliminary step, an estimate of the position

of the centre of the bore in X,Y,and Z coordinates may be made, by taking measurements of points at least at three positions around the surface, from which the position of the centre can be calculated in known manner, and using a relevant default probe transformation matrix as a starting point to convert the probe a,b,c outputs into machine X,Y,Z coordinates. This step may be useful because the next step of the calibration method requires the bore to be contacted while the machine is driven in a direction which is as near to the radial direction as possible. However, it is not important that the position of the centre of the circle is known accurately at this stage. This step may therefore not be necessary particularly if the nominal position, size and orientation of the bore are sufficiently accurate.

As explained above any slippage occurs in the local plane of the surface. Thus it has zero component in the true radial direction, and only a very small component in the approximate radial direction. Also, once the outputs of the measuring devices in the probe have been zeroed, or calibrated with the probe in its undeflected state, all probe measurements made with the stylus in its undeflected state will be substantially free from probe errors.

Since it is not normally possible to make any measurements directly when the stylus has just contacted a surface and before the stylus has deflected, and some stylus deflection is inevitable, the invention makes use of the method described in European Patent Specification No. 599513 of extrapolating the machine XY and Z readings back to the point at which the probe deflection readings are zero but with some added novel refinements.

Since nominally the probe deflection direction is known,(ie it should be the opposite of the direction of movement of the machine), and provided a moderately accurate probe transformation matrix can be supplied for converting the a,b,c probe deflection outputs to incremental X,Y,Z

coordinates, the approximate radial component of probe deflection for any touch can be calculated. Therefore, when first measuring a circle in a bore in a part, for each touch around the circle, a first estimate is made of the radial direction from the centre of the circle to the targeted touch point. This determination can be made from the approximate centre position established in the preliminary step outlined above.

In accordance with the method of the invention the probe stylus is driven into contact with the surface of the bore in a direction which is nominally normal to the surface of the bore until the predetermined stylus deflection is reached. The magnitude of this deflection is simply determined by the need to obtain enough data to find a good zero point.

As described above, once the required deflection of the stylus has been achieved, the machine is reversed while simultaneously recording the outputs of the measuring devices of the machine and of the measuring transducers in the probe.

The process is repeated for a number of other points around the surface of the bore, for example, at least 9 but preferably 50 or more are taken to achieve a reasonable distribution around the surface.

Then for each touch, using the probe transformation matrix, the nominal radial component of probe deflection is calculated against the nominal radial component of the machine movement. This will give two series of points in approximately straight lines joined by a transient section as the stylus tip leaves the surface,(see Fig 2) and for each series a best fit straight line is calculated. To improve the accuracy of the best fit straight line calculation, points in the transient region near the intersection are preferably omitted.

The just contact position used in the method is defined as the intersection between these two straight lines. The first line has nominally unit slope being the normal component of the probe deflection versus the normal component of machine movement. In an ideal situation these two components should have a 1 to 1 relationship. The second straight line has zero slope, and is the probe deflection after the stylus has left the surface (i.e. zero for a fully zeroed probe) versus the normal component of machine movement. The just contact positions for each of the points around the bore are referred to in machine co-ordinates as the X_0, Y_0, Z_0 positions.

In case the commanded radial directions were in error, it may be useful to iterate as follows: From the newly acquired set of X_0, Y_0, Z_0 positions a new "actual" centre of the circle can be calculated, and a new radial direction for each touch may be determined,(ie from the actual centre to each of the X_0, Y_0, Z_0 positions). New radial components of probe deflection are calculated, new X_0, Y_0, Z_0 points found, and a new centre found and this process is continued until the changes become acceptably small.

However, whilst the normal component relative to the surface of the artefact (radial in the above example when measuring a bore) can be readily found as described above in machine XY and Z coordinates, the same is not necessarily true of the probe outputs unless all of the probe design, construction, and transformation matrix are very accurate. Errors can give rise to the situation illustrated in Figs 3 and 4 where it can be seen that a typical sequence of nominally radial probe deflection components do not necessarily form a straight line. Even using a best fit straight line estimate through the points can give rise to significant errors in the true point of intersection. Thus as an alternative to the above-described analysis technique for finding a new centre, an alternative technique which can be used according to a

novel feature of the invention is to analyse the radial deflection plot of the probe for the straightness errors illustrated in Fig 4, and to rotate the direction (in 3D) until the plot has minimum straightness error.

This can be achieved starting from almost any orientation of probe transformation matrix or any non-radial probing direction by using an algorithm which reviews the accumulated data for the 3D direction of maximum slope in the probe deflection versus the machine radial position plot, irrespective of the apparent direction of probe deflection. The straightness of this plot is assessed. If the error is less than a predetermined tolerance, while the slope is sufficiently close to unity, the extrapolation of this line to the zero slope line will give the intersection point to the required accuracy. If the straightness error is excessive then the algorithm searches for another direction which appears straighter and still has the required slope. The straighter the line gets the more truly normal the direction must be, and the more accurate the extrapolation will be.

The above-described measurement process will produce accurate measurements of the positions of the datum points which contain minimal probe errors, despite probe slippage due to CMM and/or probe errors. From these measurements the centre and radius of the bore can be accurately determined.

Once the positions of the datum points have been accurately determined, the final stage of the calibration can be undertaken.

The bore is scanned several times at a predetermined finite probe stylus deflection, and at a relatively slow speed, ensuring that the probe stylus passes though the same 50 or more datum points.

During the scanning step, the outputs of the measuring transducers of the probe in the a,b, and c axes are transformed into incremental values of X,Y,and Z using the probe transformation matrix established above.

The differences between the measurements of the positions of the datum points obtained during the scans and said datum measurements are noted from scan to scan.

The scanning motions nominally through the datum points are repeated at the same nominal stylus deflection, and at greater and greater speeds until the variation in the recorded differences in the measurements between two scans at the same speed becomes excessive relative to a defined tolerance. The last speed at which the variation in the differences fell within the defined tolerance is recorded as the maximum scanning speed.

It is to be understood that the scanning process may start at high speed and be repeated at higher or lower speed depending on the results.

Once the maximum scanning speed has been established in this final stage, a map of the positional errors at the datum points is stored along with the data relating to the scanning speed, the particular artefact or feature, the particular CMM, the particular probe and stylus configuration, and the probe deflection used.

This map, and associated data, may be stored in the machine's computer, or outside the machine, as part of the part program relating to the specific workpiece.

It can be seen that the method of the invention avoids the need to calibrate separately the probe and the machine, thus saving time and cost in the development of algorithms for faster and more accurate system performance.

Also for the machine user, there are significant time savings by integrating probe calibration, probe static and dynamic mapping and CMM dynamic mapping into one (automatic) operation, and ultimately being able to scan at faster speeds.

Although the invention has been described with reference to the scanning of a circle within a bore, which is a two dimensional problem, the method is more generally applicable and can be used to scan other artifacts or features, including planes or three dimensional artifacts.

Also, although operators of CMMs will usually wish to scan artifacts at the highest scanning speed there is no reason why the data maps recorded at the different scanning speeds should not be stored to enable corrections to be made to scanning data taken at different speeds.

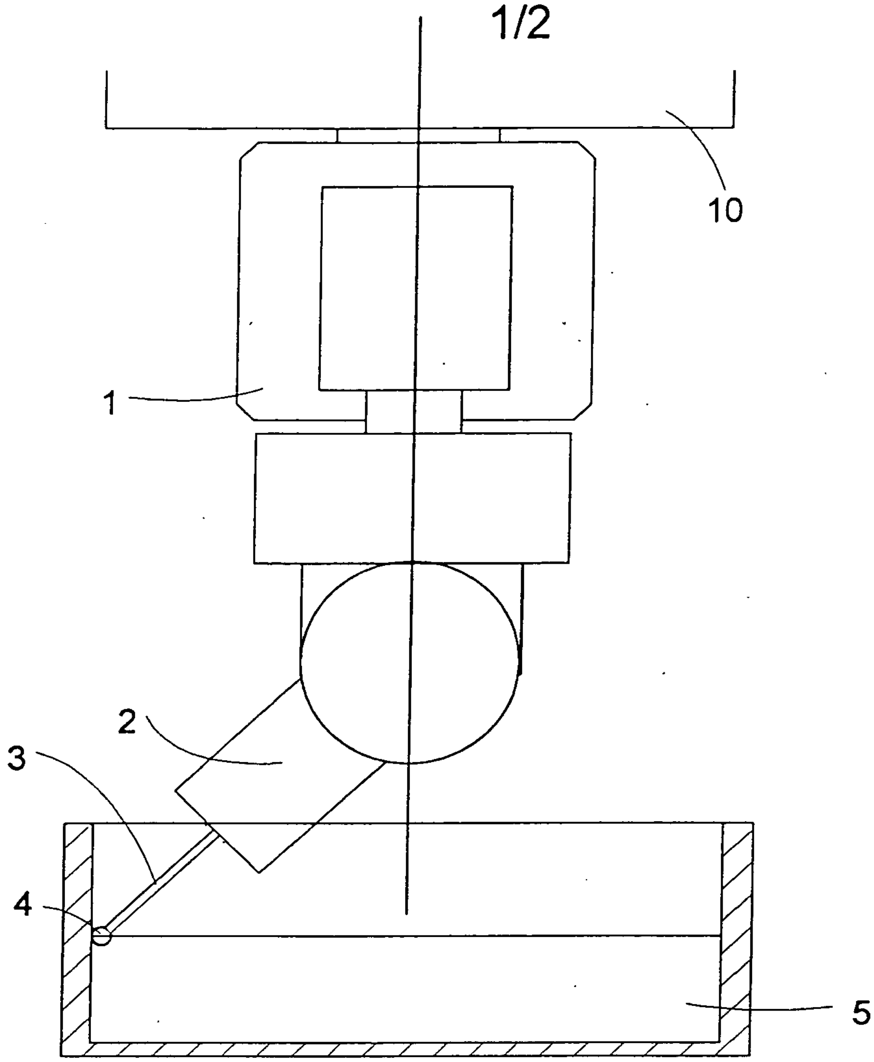

Fig1

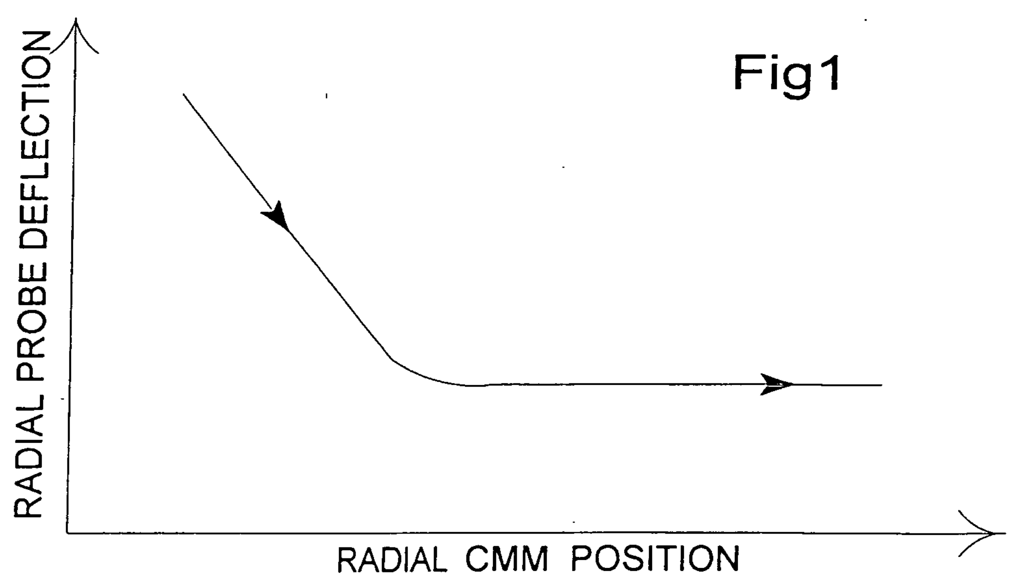

Fig2

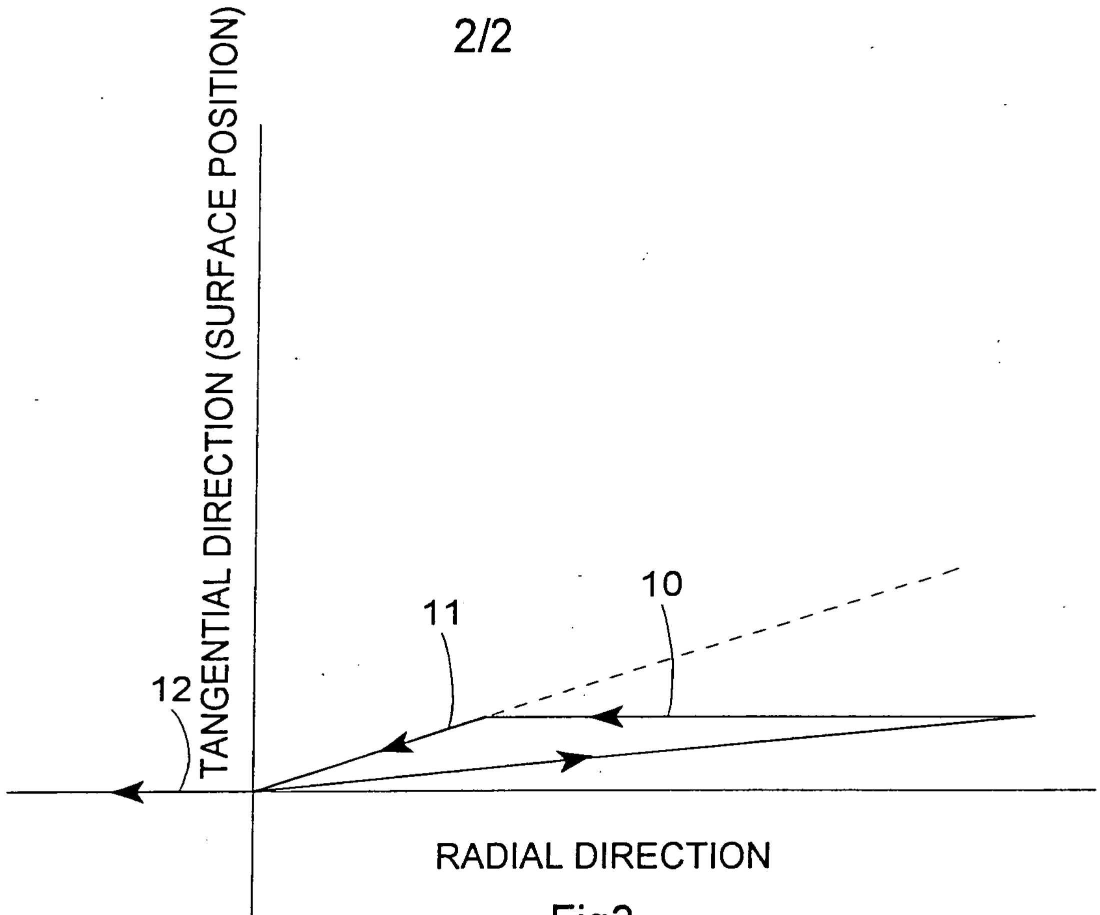

Fig3

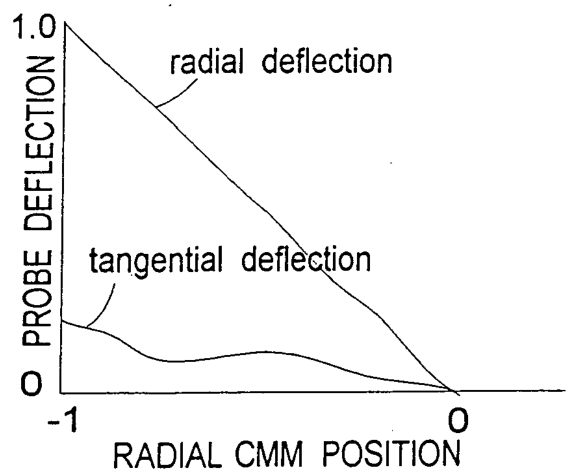

Fig4a

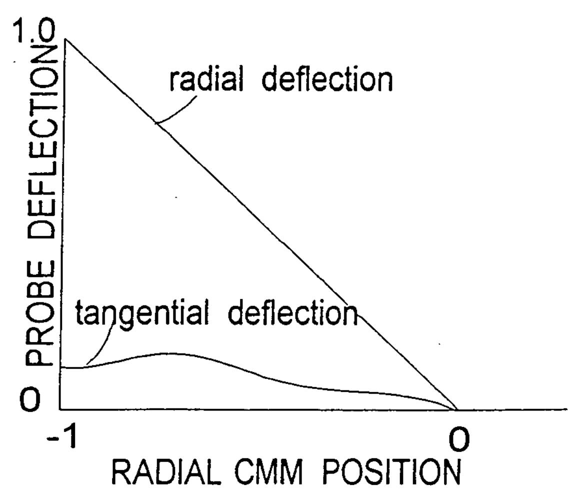

Fig4b